

# Evidence for outflows in $z \sim 5.5$ galaxies with ALMA

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## ABSTRACT

We present the first attempt to detect outflows from galaxies approaching the Epoch of Reionization (EoR) using a sample of 9 star-forming ( $5 \lesssim \text{SFR} \lesssim 70 \text{ M}_{\odot} \text{ yr}^{-1}$ )  $z \sim 5.5$  galaxies for which high-quality spectra of the [CII]158  $\mu\text{m}$  line have been previously obtained with ALMA. We first fit each line with a Gaussian function and compute the residuals by subtracting the best fitting model from the data. We combine the residuals of all sample galaxies and find that the total signal is characterized by a flux excess that can be ascribed to broad wings of the [CII] line, which we interpret as a signature of starburst-driven outflows. The inferred outflow rate is  $\dot{M} \simeq 20 \text{ M}_{\odot} \text{ yr}^{-1}$ . Our interpretation is consistent with results from zoomed hydro-simulations of *Dahlia*, a  $z \sim 6$  galaxy ( $\text{SFR} \sim 100 \text{ M}_{\odot} \text{ yr}^{-1}$ ) whose feedback-regulated star formation results in an outflow rate  $\dot{M} \sim 30 \text{ M}_{\odot} \text{ yr}^{-1}$ . These results suggest that starburst-driven outflows are in place in the EoR. Deeper observations of the [CII] line in the galaxies of this sample are required to better characterize stellar feedback at high- $z$  and to understand the role of outflows in shaping early galaxy formation.

**Key words:** galaxies: ISM - galaxies: evolution - galaxies: high-redshift

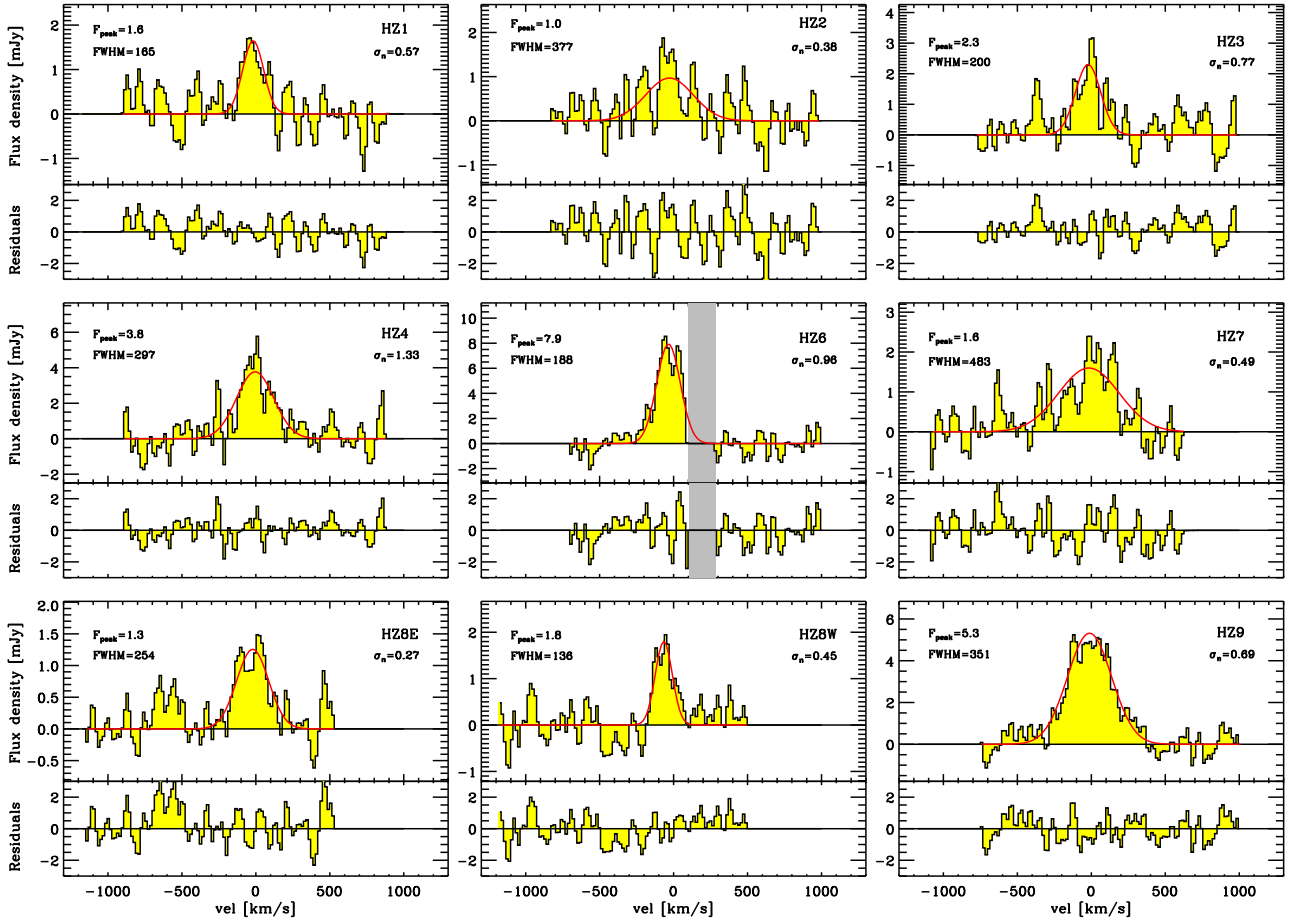
## 1 INTRODUCTION

Massive stars profoundly affect the interstellar medium (ISM) of galaxies by injecting energy and momentum in the gas. This occurs via radiation pressure, stellar winds, photoionization, and supernovae (Dekel & Silk 1986; Mac Low & Ferrara 1999; Murray et al. 2011). As a result the gas is heated and ionized, and it becomes turbulent. Moreover, a substantial fraction of the ISM can be cast into the halo (Hopkins et al. 2012; Pallottini et al. 2014b; Liang et al. 2016) and the intergalactic medium (IGM), thus enriching these components with freshly produced heavy elements (Oppenheimer & Davé 2006; Pallottini et al. 2014a). Outflows also play a key role in the life-cycle of galaxies, as they control star formation by regulating the amount of gas available to form stars. On cosmological scales, outflows are thought to shape the faint-end of the galaxy luminosity function up to the highest redshifts at which galaxies can be observed (Bouwens et al. 2014; Dunlop 2013). This com-

plex network of physical processes is collectively known as “feedback”.

Theoretically, modeling feedback represents a formidable challenge. This is because its ab-initio implementation in cosmological simulations is hampered by the range of scales (from Mpc to sub-pc; Agertz et al. 2013) involved in the problem, and also by the complexity of the physical network. Nevertheless, some simple scalings with global properties of galaxies have provided at least a phenomenological link to observations (Davé et al. 2012; Dayal et al. 2014).

Observations provide crucial insights and guidance into outflow physics and driving. The most studied local starburst galaxy, M82, shows a prominent biconical, multiphase outflow. X-ray observations suggest the coexistence of hot ( $\sim 10^7 \text{ K}$ ) gas together with a warm ( $\sim 10^3 \text{ K}$ ) H $\alpha$ -emitting phase (Lehnert et al. 1999) in which cold ( $\sim 10 \text{ K}$ ), molecular clumps are embedded, as revealed by CO observations (Walter et al. 2002). Evidence of outflows from local dwarf



**Figure 1.** [CII] emission lines observed with ALMA by C15 (yellow shaded regions). The red solid lines represent the single Gaussian fit to the data. For each galaxy, the best fit parameters (FWHM,  $F_{\text{peak}}$ ) and the noise ( $\sigma_n$ ) are reported; the normalized residuals are shown in the bottom panels by the yellow shaded regions; the gray shaded region in HZ6 represents a frequency range in which the atmospheric transmission shows an enhanced dip in the case of  $p_{\text{vw}} = 2$  mm.

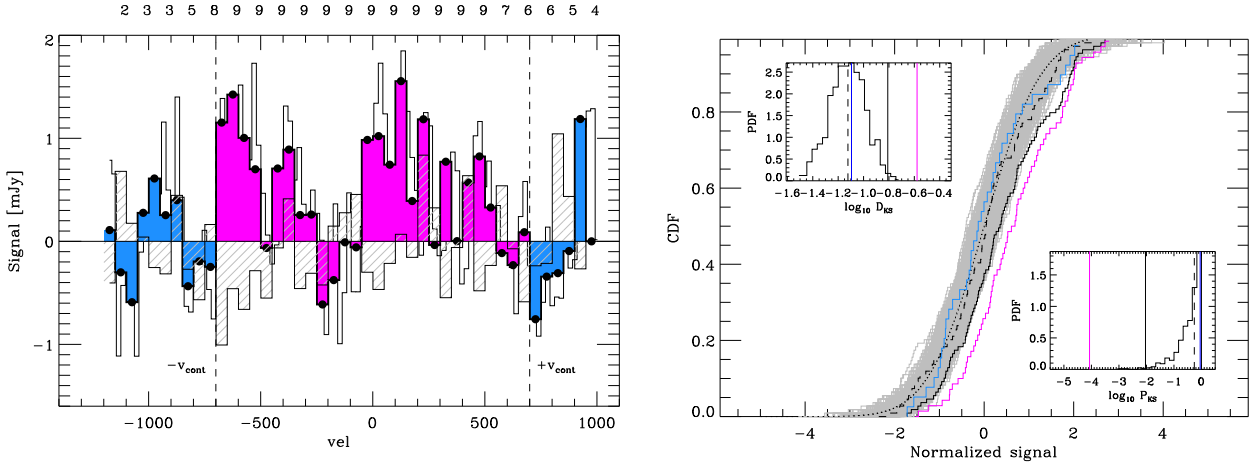
galaxies are also abundant (e.g. Martin et al. 2002; see also review by Veilleux et al. 2005). Finally, very fast (up to 1000–2000 km/s) AGN-driven outflows of molecular gas, extending on kpc scales, have been found in a dozen dusty star forming galaxies (Veilleux et al. 2013; Cicone et al. 2014; Feruglio et al. 2015).

At higher redshifts, detecting outflows becomes much more difficult. However, thanks mostly to absorption line spectroscopy, the presence of powerful outflows in galaxies close to the peak of the cosmic star formation ( $z \simeq 2 - 3$ ), has been firmly assessed (Shapley et al. 2003; Steidel et al. 2010; Kacprzak et al. 2014; Rubin et al. 2014; Heckman et al. 2015; Schroetter et al. 2015). Pushing observations into the Epoch of Reionization (EoR,  $z > 6$ ) is clearly the next frontier. This would be particularly important for several reasons. First, quasar absorption line experiments have shown that the IGM is already substantially enriched by the end of the EoR (D’Odorico et al. 2013), thus bringing a strong argument in favor of widespread galactic outflow activity. Second, a consensus exists that reionization has been primarily driven by ionizing photons produced by low-mass galaxies (Choudhury & Ferrara 2007; Choudhury et al. 2008; Finkelstein et al. 2012; Mitra et al. 2012; Robertson et al.

2015; Mitra et al. 2015; Bouwens et al. 2015) which are the most sensitive to feedback effects. Thus, outflows have likely regulated the reionization process both by modulating star formation, and the escape of LyC photons through the resulting hot cavities.

In this paper we present the first attempt to use ALMA data to detect outflows from galaxies in the EoR. Specifically, we concentrate on a recently studied (Capak et al. 2015, C15 hereafter) sample of 9 star forming galaxies ( $5 \lesssim \text{SFR} \lesssim 70 \text{ M}_{\odot} \text{ yr}^{-1}$ ) at high- $z$  ( $5.2 \lesssim z \lesssim 5.7$ ), characterized by stellar masses  $\sim 10^{10} \text{ M}_{\odot}$  for which high-quality spectra of the [CII]158  $\mu\text{m}$  line have been obtained at an angular resolution of  $\sim 0.6''$ , corresponding<sup>1</sup> to  $\sim 3.7$  kpc at  $z \sim 5.5$ . Encouraged by the success in detecting outflows from high- $z$  quasars using sub-mm lines (Maiolino et al. 2012; Cicone et al. 2015), we have refined such technique and applied it to the C15 sample. We consider HZ8 and its “companion”

<sup>1</sup> In this work we assume a  $\Lambda$ CDM model with cosmological parameters compatible with *Planck* results:  $\Omega_{\Lambda} = 0.692$ ,  $\Omega_m = 0.308$ ,  $\Omega_b = 0.0481$ , Hubble constant  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$  with  $h = 0.678$ , spectral index  $n = 0.967$ ,  $\sigma_8 = 0.826$  (Planck Collaboration et al. 2014).



**Figure 2.** **Left panel:** The coloured histogram shows  $R^{\text{tot}} \times \langle \sigma_n \rangle$ , i.e. the combined normalized residuals, multiplied for the mean value of the noise of all galaxies  $\langle \sigma_n \rangle = 0.7$  mJy. The magenta region refers to pixels characterized by  $|v| < v_{\text{cont}}$ , where  $v_{\text{cont}} = 700$  km s $^{-1}$ , while the blue region represents the region used for the noise determination, namely  $|v| > v_{\text{cont}}$ . The gray hatched histogram represents  $G^{\text{tot}}$ , i.e. the combined standard normal deviates (see footnote <sup>3</sup>). Both signals have been rebinned to 50 km s $^{-1}$ . For each spectral bin we report, on the top of the spectrum, the number of galaxies that contribute to the corresponding flux. The thin solid black line shows  $R^{\text{tot}} \times \langle \sigma_n \rangle$  at a resolution of 20 km s $^{-1}$ . **Right panel:** Cumulative distribution functions (CDFs) of  $R^{\text{tot}}$  (solid black line) and  $G^{\text{tot}}$  (dashed black line), rebinned to a spectral resolution of 20 km s $^{-1}$ . The magenta (blue) line shows the CDF of  $R^{\text{tot}}$  computed in the velocity range  $|v| < v_{\text{cont}}$  ( $|v| > v_{\text{cont}}$ ). The shaded gray region represents the CDFs of 500 *standard normal deviates*, while the dotted line denotes the error function. See the main text for a description of the insets.

**Table 1.** Results for the Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) tests.

	KS probability	KS statistics	AD statistics
$G^{\text{tot}}$	0.55	0.07	0.01
$R^{\text{tot}}$	$4 \times 10^{-3}$	0.17	0.12
$R^{\text{tot}} ( v  < v_{\text{cont}})$	$3 \times 10^{-5}$	0.28	0.31
$R^{\text{tot}} ( v  > v_{\text{cont}})$	0.90	0.08	0.02

galaxy HZ8W as two distinct sources. We do not consider the quasar HZ5, and the galaxy HZ10 since its [CII] emission line is located at the edge of the observed spectrum. In the following, we report the first tentative evidence of outflows in galaxies less than a billion years from the Big Bang.

## 2 METHOD

For each galaxy in the C15 sample, we fit the [CII] emission line ( $F_{\text{obs}}$ ) with a Gaussian function ( $F_{\text{mod}}$ ), whose free parameters are the full width at half maximum, FWHM, the peak flux,  $F_{\text{peak}}$ , and the center velocity,  $v_0$ . Moreover, we quantify the noise ( $\sigma_n$ ) of the spectrum by computing the standard deviation of the observed flux in pixels characterized by a velocity  $|v| > v_{\text{cont}}$ , where<sup>2</sup>  $v_{\text{cont}} = 700$  km s $^{-1}$ . We find  $0.3 < \sigma_n / [\text{mJy}] < 1.3$  with a mean value  $\langle \sigma_n \rangle = 0.7$  mJy. Finally, we compute the residuals by subtracting

the best fitting model from the observed spectrum, and normalize them to the noise,  $R = (F_{\text{obs}} - F_{\text{mod}}) \sigma_n^{-1}$ . As a sanity check of the method, for each galaxy, we also compute a *standard normal deviate*<sup>3</sup>, hereafter called  $G$ .

In Fig. 1 we show the results from the above procedure for each galaxy in the sample. In each panel, we report the observed spectrum (yellow shaded region), the Gaussian best fit (red line) and the normalized residual (yellow shaded region in the sub-panel). For each galaxy, we specify  $F_{\text{peak}}$  and the FWHM of the [CII] line resulting from the fit, as well as  $\sigma_n$ . We have removed from the observed spectra those pixels where the atmospheric transmission shows enhanced dips at the relevant frequencies, assuming  $pwv = 2$  mm for the precipitable water vapor<sup>4</sup>. This has been necessary only for HZ6, as shown by the gray shaded region.

The quality of the spectra is not sufficient to detect outflows in individual galaxies. We thus combine both  $R$  and  $G$  of all galaxies into single arrays:

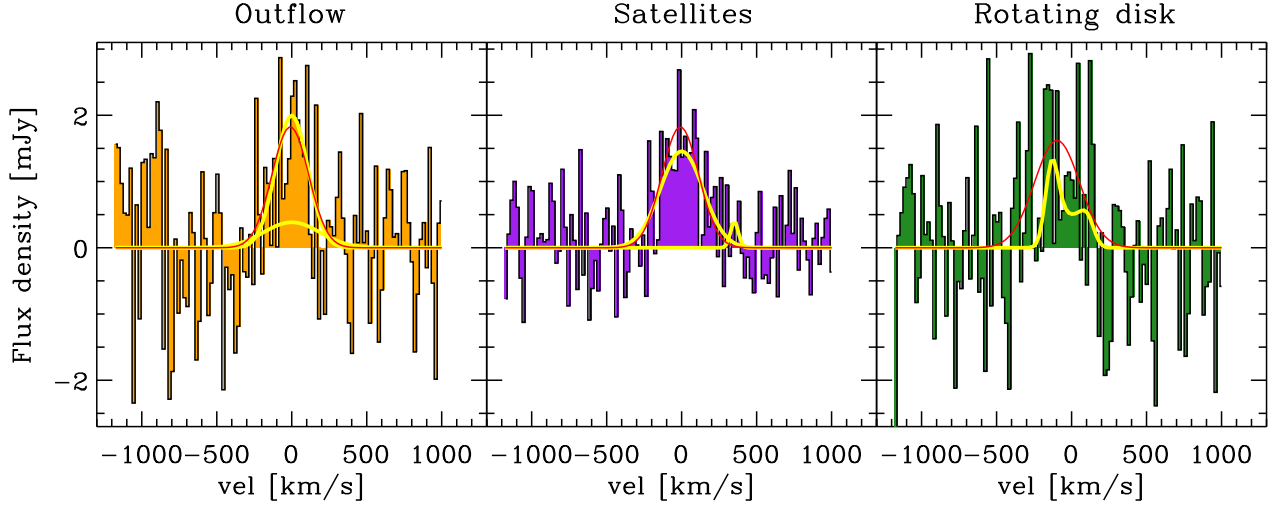
$$R^{\text{tot}}(v) = \frac{1}{n_{\text{gal}}} \sum_{j=1}^{n_{\text{gal}}} R^j(v); G^{\text{tot}}(v) = \frac{1}{n_{\text{gal}}} \sum_{j=1}^{n_{\text{gal}}} G^j(v). \quad (1)$$

The stacked signal, rebinned to 50 km s $^{-1}$ , and multiplied for  $\langle \sigma_n \rangle$  is shown in the left panel of Fig. 2, where we have differentiated pixels characterized by  $|v| > v_{\text{cont}}$  (blue shaded region), from those with  $|v| < v_{\text{cont}}$  (magenta shaded region). For each spectral bin, on top of the spectrum, we report the number of galaxies contributing to the corresponding flux. In the same figure, we plot  $G^{\text{tot}} \times \langle \sigma_n \rangle$  with an hatched gray region, rebinned to 50 km s $^{-1}$ , and  $R^{\text{tot}} \times \langle \sigma_n \rangle$

<sup>2</sup> The value of  $v_{\text{cont}}$  has been chosen in order to minimize the contamination by broad wings. However, its specific value does not affect the results of our study.

<sup>3</sup> A *standard normal deviate* is a random number extracted by a Gaussian distribution having mean equal to zero and standard deviation equal to one.

<sup>4</sup> This is a conservative assumption since the actual values for these observations were  $pwv = 0.2 - 1.9$  mm (mostly  $< 1$  mm).



**Figure 3.** Examples of synthetic spectra for the *Outflow* (left panel), *Satellites* (middle panel), and *Rotating disk* (right panel) scenarios. The thick yellow lines represent the original synthetic spectra, while coloured shaded regions show the final spectra, after adding noise. The solid red line represent the best-fit *single* Gaussian profile.

with a solid black line at a resolution of  $20 \text{ km s}^{-1}$ . We underline that the final stacked signal takes into account the differences between individual sources, since for each galaxy we subtracted the individual fit from the observed spectrum and normalized the residual to its own  $\sigma_n$ . Both in individual sources and in the stacked spectrum, the analysis takes into account the removal of a residual continuum term due to faint, individually undetected continuum or residuals in the subtraction.

If the observed spectra were completely determined by a single Gaussian [CII] emission line, the flux density of  $R^{\text{tot}}$  should consist simply of noise. In other words, both  $R^{\text{tot}}$  and  $G^{\text{tot}}$  should be described, by construction, by a *standard normal deviate*. We compute the cumulative distribution function (CDF) both of  $R^{\text{tot}}$  and  $G^{\text{tot}}$ , at a resolution of  $20 \text{ km s}^{-1}$ , and we compare them with the error function:

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \quad (2)$$

that describes the CDF of a *standard normal deviate*.

The resulting CDFs of  $R^{\text{tot}}$  (solid black line) and  $G^{\text{tot}}$  (dashed black line) are shown in the right panel of Fig. 2. The blue and magenta lines show the CDF of  $R^{\text{tot}}$  for  $|v| > v_{\text{cont}}$  and  $|v| < v_{\text{cont}}$ , respectively, while the gray-shaded region is the result of the CDFs computed for 500 *standard normal deviates*. Finally, the dotted line represents the CDF described by eq. 2. While the CDF of  $R^{\text{tot}}$  strongly differs from the  $G^{\text{tot}}$  CDF (particularly for  $|v| < v_{\text{cont}}$ ), the latter is, as expected, well within the gray-shaded regions. This sanity check ensures that the method adopted does not artificially introduces any deviation from a *standard normal deviate*.

To quantify the deviation of the CDFs from the error function *erf*, we apply the Kolmogorov-Smirnov (KS) test to our data: we compute i) the KS statistics, namely the maximum deviation ( $D_{\text{KS}}$ ) of the observed CDFs from the *erf* and the ii) the KS probability ( $P_{\text{KS}}$ ); small values of the KS

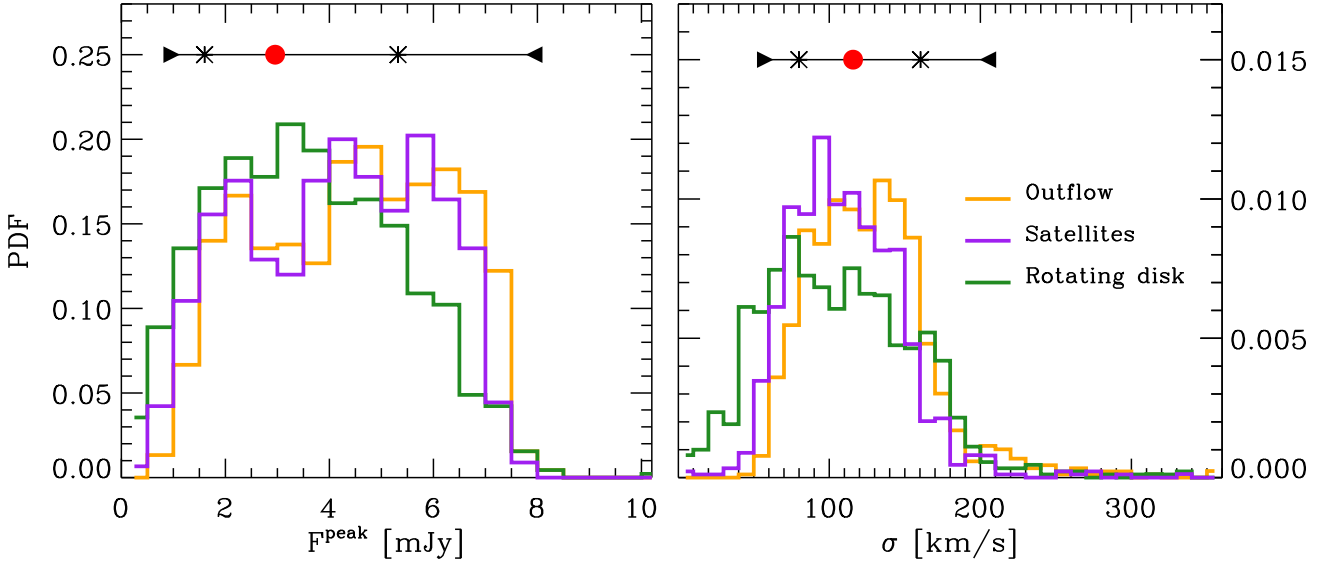
**Table 2.** Parameter ranges for Monte Carlo simulations of synthetic profiles

	<i>Outflow</i>	<i>Satellites</i>	<i>Rotating disk</i>
$F_{\text{Peak}}^{\text{narrow}}$ [mJy]	1–7	–	–
$\sigma_{\text{narrow}}$ [km s $^{-1}$ ]	60–160	–	–
$F_{\text{Peak}}^{\text{broad}}$ [mJy]	0.3–0.6	–	–
$\sigma_{\text{broad}}$ [km s $^{-1}$ ]	100–500	–	–
# satellites	–	1	–
$F_{\text{Peak}}^{\text{sat}}$ [mJy]	–	0.1–0.4	–
$\sigma_{\text{sat}}$ [km s $^{-1}$ ]	–	20–50	–
$F_{\text{Peak}}^{\text{RD}}$ [mJy]	–	–	1–7
$v_c$ [km s $^{-1}$ ]	–	–	50–200
$\sigma_{\text{gas}}$ [km s $^{-1}$ ]	–	–	8–50

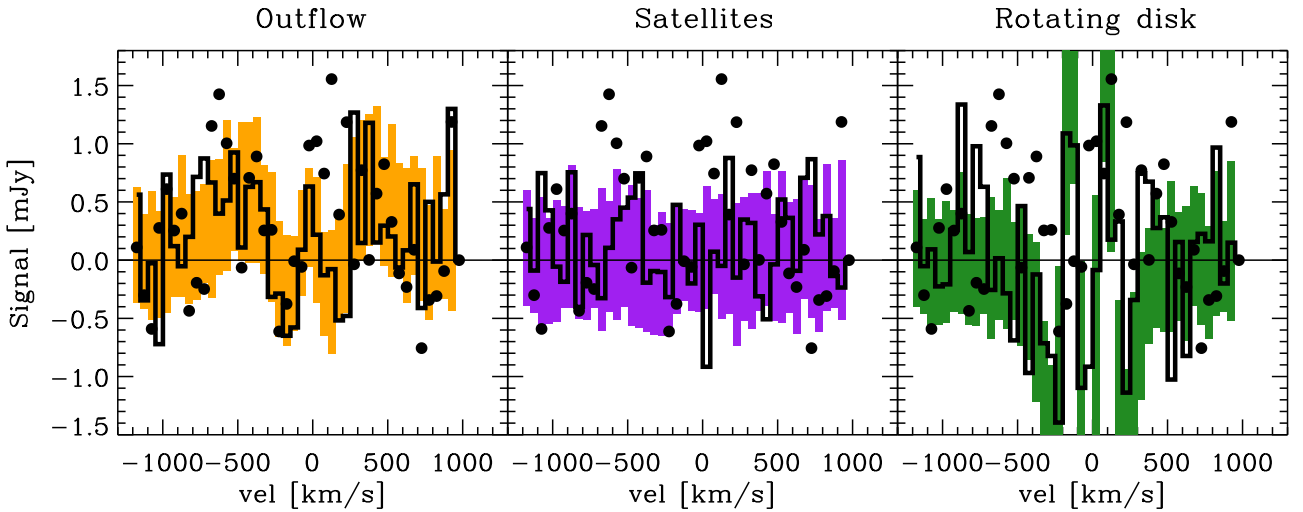
probability imply that a CDF is significantly different from the *erf*. We apply the KS test to the CDF of  $G^{\text{tot}}$  and  $R^{\text{tot}}$  and we report the results in Tab. 1. Moreover, we quantify the deviation of the CDFs of the random Gaussian deviates  $G_i$  from the error function *erf*. In the bottom right and top left insets of Fig. 2 (right panel), we show the probability distribution function (PDF) of  $D_{\text{KS}}^{G_i}$  and  $P_{\text{KS}}^{G_i}$ , respectively, along with the results shown in Tab. 1. The residual flux clearly exceeds that of a *standard normal deviate*. This result is also confirmed by applying the Anderson-Darling test to the data. According to this test, a sample is significantly different from a random gaussian deviate if the *AD* statistics is larger than 0.05 (see the third column in Tab. 1).

### 3 INTERPRETING THE FLUX EXCESS

The reported flux excess suggests that a single Gaussian model does not accurately describe the [CII] line profiles



**Figure 4.** Probability distribution functions (PDF) of the flux peak ( $F^{\text{peak}}$ , left panel) and width ( $\sigma$ , right panel) of the single Gaussian component that provides the best-fit of the synthetic spectra for the models analysed. We plot the PDF for the *Outflow*, *Satellites* and *Rotating disk* scenarios with an orange, green and violet line, respectively. As a reference, for both  $F^{\text{peak}}$  and  $\sigma$  we plot the min/1<sup>st</sup> quartile/mean/3<sup>rd</sup> quartile/max values obtained from the best-fit of the C15 sample with right triangle/asterisk/red circle/asterisk/left triangle, respectively.



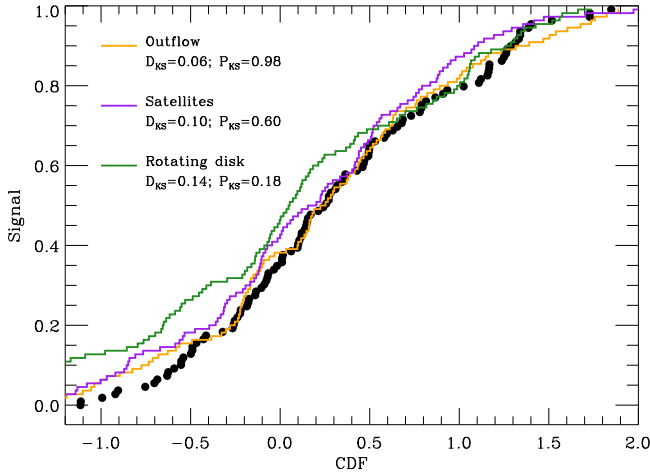
**Figure 5.** Combined residuals for the synthetic samples (see left panel of Fig. 2). Filled black circles refer to the C15 sample. The black thick lines represent the realizations that provide the best agreement with data, while the coloured shaded regions quantify the  $1\sigma$  dispersion over the 100 realizations.

observed in the  $z \sim 5.5$  galaxies from C15. Several effects can explain such discrepancy:

- if supernova-driven outflows are present as predicted (e.g. Pallottini et al. 2016, see also Sec. 4), broad wings superposed to a narrower Gaussian core should feature the [CII] line profile;
- a multi-peaked profile might result from the collective emission of satellite galaxies (e.g. Vallini et al. 2013, 2015);
- if a rotating disk is present, the line profile might take a double-horned profile (e.g. de Blok & Walter 2014).

To analyze these possibilities, we produce 3 sets of 900 Monte Carlo simulations of [CII] emission lines with different profiles, depending on the scenario considered (see Sec. 3.1, 3.2, 3.3 below). To simulate the observed noise, we add to each synthetic spectrum a gaussian deviate with zero mean and  $0.3 < \sigma_n / [\text{mJy}] < 1.3$ . For each scenario, we divide the full synthetic sample in 100 realizations of 9 galaxies, and we apply to each sub-sample the same method described in Sec. 2: we first fit each synthetic profile with a single Gaussian (presented in Fig. 4 in next Sec.); then, we normalize the





**Figure 6.** CDF of the residuals for the synthetic samples (see right panel of Fig. 2). Filled black circles refer to the CDF of C15 sample. Coloured lines represent the realizations that provide the best agreement with data. We also report the results of the KS test (KS statistics,  $D_{KS}$ , and KS probability,  $P_{KS}$ ) between the observed CDF and the simulated ones.

residual to  $\sigma_n$ ; finally, we stack the 9 simulated residuals into a single signal and we multiply it for  $\langle\sigma_n\rangle$  (presented in Fig. 5 in next Sec.).

### 3.1 Outflow

In this first scenario, synthetic [CII] emission lines are constituted by the sum of a narrow Gaussian (defined by its peak flux  $F_{\text{peak}}^{\text{narrow}}$  and RMS  $\sigma^{\text{narrow}}$ ) plus a broad Gaussian profile ( $F_{\text{peak}}^{\text{broad}}$ ;  $\sigma^{\text{broad}}$ ). We consider the parameter ranges shown in Tab. 2. We assume the same central velocity both for the narrow and broad component. We take  $\sigma^{\text{broad}}$  by numerical simulation results (see Sec. 4).

### 3.2 Satellites

To mimic the effect of satellites on the [CII] line profiles, we consider the sum of a Gaussian profile (defined by  $F_{\text{peak}}^{\text{narrow}}$  and  $\sigma^{\text{narrow}}$ ) plus a number  $N_{\text{sat}}$  of Gaussians characterized by  $F_{\text{peak}}^{\text{sat}}$  and  $\sigma^{\text{sat}}$  (see Tab. 2).

To constrain  $\sigma^{\text{sat}}$ , we consider, as upper limit, the minimum value of  $\sigma$  in the C15 sample ( $\sigma = 50 \text{ km s}^{-1}$ ), and, as lower limit, the minimum value of  $\sigma$  found in all the [CII] emission lines detected so far at high redshift ( $\sigma = 20 \text{ km s}^{-1}$ ; Pentericci et al. 2016).

For what concerns  $F_{\text{peak}}^{\text{sat}}$ , we use the  $M_{\text{UV}} - F_{\text{peak}}$  relation presented in Pallottini et al. (2015, see their eq. 2). The UV magnitude limit of the C15 sample ( $M_{\text{UV}} > -19.94$ ) converts into an upper limit for the [CII] emission line peak ( $F_{\text{peak}}^{\text{sat}} < 0.4 \text{ mJy}$ ; see also Yue et al. 2015; Vallini et al. 2015). We note that this UV magnitude roughly corresponds to satellites with  $SFR^{\text{sat}} \sim 1 M_{\odot} \text{ yr}^{-1}$  and  $M_{*}^{\text{sat}} \sim 10^9 M_{\odot}$ . Finally, to compute the number of satellites that we expect to surround the galaxies of our sample, we adopt the halo occupation distribution model (see eq. 14 by Yue et al. 2013). The C15 sample consists of  $M_{*} \sim 10^{10} M_{\odot}$  galaxies that are

expected to be hosted in  $M_{\text{DM}} = 6 \times 10^{11} M_{\odot}$  dark matter halo. In such halo, we expect to find  $\sim 4$  satellites with  $M_{*}^{\text{sat}} \sim 10^9 M_{\odot}$ . Given that these satellites can be located at a distance up to  $r_{\text{vir}} \sim 40 \text{ kpc}$ , we find that it is very unlikely to find any of them within 1-2 beams ( $\sim 3\text{--}7 \text{ kpc}$ ) of the ALMA observations.

In our calculations, we use  $F_{\text{peak}}^{\text{sat}} = 0.1 - 0.4 \text{ mJy}$  and we assume that, for each of the C15 galaxies, the ALMA beam encloses a number of satellites  $N_{\text{sat}} = 1$  (see Tab. 2). Thus, the contribution of satellites to the observed flux excess that we compute must be considered a solid upper limit.

### 3.3 Rotating disk

To simulate the double-horned profile resulting from a rotating disk we refer to the work done by de Blok & Walter (2014, in particular see eq. 1). A double-horned profile is specified by its peak flux  $F_{\text{peak}}^{\text{RD}}$ , the disk circular velocity  $v_c$ , and the gas velocity dispersion  $\sigma_{\text{gas}}$ ; the double-horned is given by the convolution of a gaussian ( $F_{\text{peak}}^{\text{RD}}, \sigma_{\text{gas}}$ ) with the velocity profile  $\psi(v) = (v^2 - v_c^2)^{-1/2} \Theta(|v_c| - v)/\pi$ , where  $\Theta$  is the Heaviside function. We consider the parameter ranges shown in Tab. 2.

### 3.4 Results

In Fig. 3, we show one example of synthetic emission line for each scenario described above (*Outflow* in the left, *Satellites* in the middle and *Rotating disk* in the right panel).

We model each synthetic spectrum with a single Gaussian profile: in Fig. 4, we show the PDF of the best-fit Gaussian peak (left panel) and  $\sigma$  (right panel) (orange line for the *Outflow*, violet line for the *Satellites*, green line for the *Rotating disk* scenarios). As a reference, we plot the min, the 1<sup>st</sup> quartile, the mean, the 3<sup>rd</sup> quartile, and the maximum values resulting from the best-fit models of the C15 sample. The nice agreement between the observed values and the synthetic ones shows that the simulated lines have properties consistent with data.

We calculate the residuals using the best-fit Gaussians: in Fig. 5 (left/middle/right panel) we compare the observed flux excess (filled circles) with the one we obtain by applying our method to the simulated samples (*Outflow/Satellites/Rotating disk*). The black thick lines represent the realizations that provide the best agreement with data, while the coloured shaded regions quantify the  $1\sigma$  dispersion over the 100 realizations. This figure shows that our method, in the case of the *Outflow* scenario, provides residuals that are in a qualitative better agreement with observations with respect to the *Satellites* and *Rotating disk* scenarios considered.

To be more quantitative, in Fig. 6, we compare the observed CDF (filled circles) with the ones extracted from synthetic samples (orange line for the *Outflow*, violet line for the *Satellites*, green line for the *Rotating disk* scenarios). We apply the KS test between the observed and simulated CDFs and we report the results in the figure. We find that the maximum distance from the observed CDF is minimized by the *Outflow* scenario, i.e.  $D_{KS} = 0.06$ . In this case the probability that the simulated CDF reproduces the observed one is maximum and equal to  $P_{KS} = 0.98$ .

This analysis suggests that the observed flux excess can be ascribed to broad wings of the [CII] line tracing a starburst-driven outflow. In the realization that better describes the observed flux excess, the average value of the flux peak broad component is  $\langle F_{\text{peak}}^{\text{broad}} \rangle = 0.4 \pm 0.1$  mJy, while  $\langle \sigma^{\text{broad}} \rangle = 360 \pm 140$  km s<sup>-1</sup>.

As a final test, we have divided our sample in two sub-samples: S1 containing HZ1, HZ2, HZ3 and HZ7, HZ8 and HZ8W, i.e. galaxies with  $SFR < 50 M_{\odot} \text{ yr}^{-1}$ , and S2 constituted by HZ4, HZ6 and HZ9, i.e. galaxies with  $SFR \gtrsim 50 M_{\odot} \text{ yr}^{-1}$ . In both cases the deviation from a standard normal deviate is found, though the flux excess is stronger in the S2 sub-sample. This is expected as in the S2 sub-sample galaxies there are more SN available to drive outflows. However, the statistical significance of this result is limited by the small number of galaxies in the sub-samples.

#### 4 NUMERICAL SIMULATIONS

We test our results against zoomed hydro-simulations of high redshift galaxies performed with the Adaptive Mesh Refinement (AMR) code RAMSES (Teyssier 2002). These simulations are fully described in Pallottini et al. (2016, P16 hereafter); here, we summarize the aspects of the simulation that are relevant for this work.

Starting from cosmological initial conditions, we carry out a zoom-in simulation of a  $z \sim 6$  dark matter (DM) halo of mass  $\sim 10^{11} M_{\odot}$  (virial radius of  $\simeq 15$  kpc). In the zoomed-in region, the gas mass resolution is  $10^4 M_{\odot}$ , and the AMR grid is refined to spatial scales  $\simeq 30$  pc. We form stars from molecular hydrogen, following the model by Krumholz et al. (2009). Stellar feedback includes supernovae, winds from massive stars and radiation pressure (e.g. Agertz et al. 2013). We model the thermal and turbulent energy content of the gas according to the prescriptions by Agertz & Kravtsov (2015). We account for stellar energy inputs and winds that depend both on time and stellar populations (e.g. Kim et al. 2014).

At  $z \sim 6$ , the DM halo hosts a galaxy (named *Dahlia*) characterized by a stellar mass  $M_{\star} \sim 10^{10} M_{\odot}$  and a SFR  $\sim 100 M_{\odot} \text{ yr}^{-1}$ . In the top panels of Fig. 7, we show a slice of the density and metallicity fields (left and right, respectively) along with the velocity field orthogonal to the line of sight. Within a radial distance  $r \lesssim 5$  kpc from *Dahlia*'s center, the gas has an average density of  $n \simeq 10 \text{ cm}^{-3}$ , it is enriched to  $Z \simeq 10^{-1} Z_{\odot}$ , and rotates with a velocity  $v_c \sim 100 \text{ km s}^{-1}$ . At  $5 \lesssim (r/\text{kpc}) \lesssim 15$ , *Dahlia* is surrounded by a bubble of low density ( $n \simeq 10^{-1} \text{ cm}^{-3}$ ), low metallicity ( $Z \simeq 10^{-2} Z_{\odot}$ ) gas, outflowing at a speed  $v \sim 100 \text{ km s}^{-1}$ . In the same region, dense ( $n \simeq 1 \text{ cm}^{-3}$ ) and almost metal free  $Z \simeq 10^{-3} Z_{\odot}$  filaments are infalling with a velocity  $v \sim 100 \text{ km s}^{-1}$ . These filaments penetrate *Dahlia*'s circumgalactic medium at a distance of  $\sim 7$  kpc (half of the virial radius), mixing with such component and becoming progressively more isotropic.

To better quantify our analysis, we compute the mass flow rate<sup>5</sup> ( $\dot{M}$ ) and the PDF of the radial velocity ( $v_r$ ) at

distances<sup>6</sup>  $r \simeq 0.1$  kpc,  $r \simeq 2$  kpc and  $r \simeq 15$  kpc. The results are shown in Fig. 7, in the bottom left and right panels, respectively.

At the center ( $r \simeq 0.1$  kpc), we find high radial velocities ( $\sim 500 \text{ km s}^{-1}$ ) for both the infall and outflow<sup>7</sup>. As the infall fuels gas directly at the center, *Dahlia*'s SFR is mostly concentrated around  $r \simeq 0.1$  kpc. Via stellar feedback, this in turn causes high outflows velocities. Within  $r \simeq 2$  kpc the mass inflow and the outflow rate are nearly equal ( $\sim 30 M_{\odot} \text{ yr}^{-1}$ ). Interestingly, the two rates are roughly equal also for metals. We interpret this as a result of efficient turbulent mixing between the two flows.

For  $r \gtrsim 2$  kpc the velocity depends only mildly on radius, and since the density is approximately  $\rho \propto r^{-2}$ , the observed constancy of the outflow rate is mostly a consequence of a geometrical effect.

At  $r \gtrsim 5$  kpc, the infall rate drops by a factor  $\gtrsim 10$  below the outflow rate. This is caused by the different spatial structure of the two flows: while the incoming gas rains onto *Dahlia* along narrow filaments, the outflow is essentially spherically symmetric. Note that the outflow is  $\sim 10$  times more enriched than the infall, as most of the gas is essentially of pristine composition; thus, we expect the infall contribution to [CII] emission to be negligible with respect to the outflow. The ratio mildly declines with radius because of the progressive dilution of the outflow metal content with the IGM.

The presence of peaks at  $r \sim 12$  kpc and  $r \sim 20$  kpc is due to the presence of satellite galaxies. As projection effects are in place, we underline that it is quite unlikely to find such satellites in the  $\sim 3$  kpc beam centered on the main galaxy (*Dahlia* in this case) from which the [CII] spectra is calculated in C15. From Fig. 10 by P16, we note that few ( $\sim 3$ ) molecular clouds of mass  $\sim 10^6 M_{\odot}$  are present within  $\lesssim 5$  kpc from the center of *Dahlia*; however, such clumps negligibly contribute to the [CII] emission since their typical luminosity is  $L_{\text{CII}}/L_{\odot} \simeq 10^5$  (see eq. 8 in P16), i.e. a factor  $\sim 10^3$  less than the main galaxy.

#### 5 CONCLUSIONS

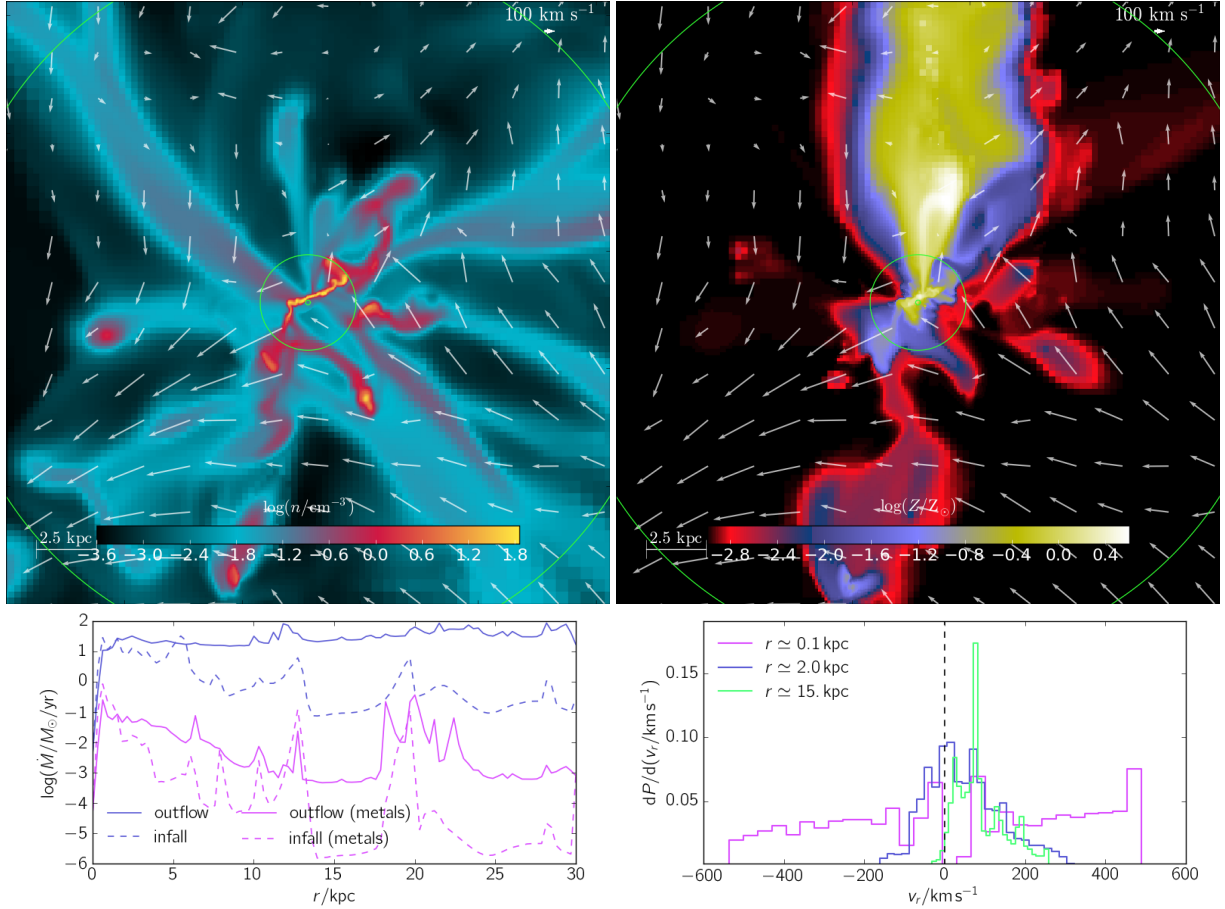
We have analyzed the [CII] emission lines obtained with ALMA (Capak et al. 2015) in a sample of 9 star-forming ( $5 \lesssim SFR \lesssim 70 M_{\odot} \text{ yr}^{-1}$ ) high- $z$  ( $5.2 \lesssim z \lesssim 5.7$ ) galaxies. We have fitted each [CII] emission line with a Gaussian function and we have computed the residual by subtracting the best fitting model from the data. By combining the residuals of all the galaxies, we have found a flux excess that can be ascribed to broad wings of the [CII] line tracing a starburst-driven outflow. In order to get a rough estimate of

surface area element,  $\rho = \mu m_p n$  is the proton mass, and  $v_r < 0$  for infalling gas and  $v_r > 0$  for outflowing gas.

<sup>6</sup> To compute the radial velocity PDF we consider spherical shells with a thickness  $\simeq 100$  pc centered at a distance  $r$  from *Dahlia*. This ensures that for each shell the PDF contains a minimum of  $\sim 100$  resolution elements.

<sup>7</sup> We use these values of radial velocity to model the  $\sigma^{\text{broad}}$  in the *Outflow* scenario presented in Sec. 3.1.

<sup>5</sup> The mass flow rate at a distance  $r$  is defined as the material crossing a sphere of radius  $r$ :  $\dot{M} = \int \rho \mathbf{v} \cdot d\mathbf{A}$ , where  $d\mathbf{A}$  is the



**Figure 7.** Slice of the density ( $n/\text{cm}^{-3}$ , **upper left panel**) and metallicity ( $Z/Z_{\odot}$ , **upper right panel**) fields centered on the simulated galaxy *Dahlia*. In both maps, the velocity field orthogonal to the line of sight is overplotted with white arrows and the spatial scale is indicated in the lower left corner. Green circles indicate a distance of  $r/\text{kpc} \simeq 0.1, 2, 15$  from the center. The **lower left panel** shows the radially averaged outflow (solid line) and infall (dashed line) rate profiles for the gas (blue) and metals (magenta). The **lower right panel** shows the PDF of the radial velocity ( $v_r$ ) calculated for the gas at distance  $r \simeq 0.1$  kpc (magenta),  $r \simeq 2$  kpc (blue),  $r \simeq 15$  kpc (green).

the outflow rate  $\dot{M}$ , we use the following equation:

$$\dot{M} = v_{\text{outfl}} \frac{M_{\text{outfl}}}{R_{\text{outfl}}}, \quad (3)$$

where  $M_{\text{outfl}} \sim 10^8 M_{\odot}$  (from eq. 1 by Maiolino et al. 2012) and  $v_{\text{outfl}} \sim 500 \text{ km s}^{-1}$ . For what concerns  $R_{\text{outfl}}$ , we assume that the spatial extent of the outflow is of the order of the radius of the deconvolved [CII] emission sizes, i.e.  $\sim 1.9$  kpc, a value consistent with the half-light radii of  $z \sim 6$  LAEs (Taniguchi et al. 2009; Malhotra et al. 2011; Shibuya et al. 2015). Through this procedure, infer an outflow rate of  $\dot{M} \sim 20 M_{\odot} \text{ yr}^{-1}$ . Given that the average star formation rate of our sample is  $\langle \text{SFR} \rangle \sim 30 M_{\odot} \text{ yr}^{-1}$ , we estimate an average loading factor  $\langle \dot{M}/\text{SFR} \rangle \sim 0.7$ , in nice agreement with the results found in local starbursts (see top left panel of Fig. 6 by Heckman et al. 2015), and comparable to the outcomes of simulations ( $\sim 0.3$  in P16). Recently, Heckman & Borthakur (2016) have analyzed a sample of low- $z$  ( $0.2 \lesssim z \lesssim 0.7$ ) galaxies characterized by a large range of SFRs ( $10^{-2} \lesssim \text{SFR}/[M_{\odot} \text{ yr}^{-1}] \lesssim 10^3$ ), and found a strong correlation between the specific SFR ( $\text{sSFR} = \text{SFR}/M_{\star}$ ) and  $v_{\text{max}}$  (see bottom left panel of their Fig. 1). From their scaling relation, we expect  $v_{\text{max}} \sim 500 \text{ km s}^{-1}$  for a  $\text{sSFR} \sim$

$3 \times 10^{-9} \text{ yr}^{-1}$ , that is once more consistent with our findings.

We test these results against state-of-the-art hydrodynamical simulations of *Dahlia* (Pallottini et al. 2016), a star forming ( $\text{SFR} \sim 10^2 M_{\odot} \text{ yr}^{-1}$ )  $z \sim 6$  galaxy. Star formation in the simulations is regulated by radiation pressure and stellar winds from massive stars, and supernovae explosions. We find that, at a distance  $r \lesssim 5$  kpc from the *Dahlia* center, the infall rate is balanced by outflowing gas with  $\dot{M} \sim 30 M_{\odot} \text{ yr}^{-1}$ . At larger distances, the outflow rate remains almost constant, while infalls are characterized by  $\dot{M} \sim 1 M_{\odot} \text{ yr}^{-1}$ .

The simulation outcomes are consistent with our interpretation of the ALMA data suggesting that starburst-driven outflows are in place in the EoR. However, we warn here that we are comparing an observed signal stacked from 9 galaxies with a single synthetic galaxy. For a more specific comparison, we urge to get deeper observations of the [CII] line in the galaxies of this sample to better characterize stellar feedback at high- $z$  and to understand its role in shaping early galaxy formation.



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